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Assessment of renewable energy reserves in Taiwan

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ABSTRACT

Since Taiwan imports more than 99% of energy supply from foreign countries, energy security has always been the first priority for government to formulate energy policy. The development of renewable energy not only contributes to the independence of energy supply, but also achieves benefits of economic development and environmental protection. Based upon information available to public, the present paper reassesses reserves of various renewable energies in Taiwan. The assessment includes seven kinds of renewable energies, namely, solar energy, wind power, biomass energy, wave energy, tidal energy, geothermal energy and hydropower, which are all commercialized and matured in terms of current technologies. Other renewable energies, which have not proven as matured as the aforementioned ones, are only assessed preliminarily in this paper, such as second generation of biomass, deep geothermal energy, the Kuroshio power generation and ocean thermal energy conversion.

According to the estimation of this paper, the reserve of wind energy, up to 29.9 kWh/d/p (i.e., kWh per day per person), is the largest one among seven kinds of renewable energies in Taiwan, followed by 24.27 kWh/d/p of solar energy, 4.55 kWh/d/p of biomass, 4.58 kWh/d/p of ocean energy, 0.67 kWh/d/p of geothermal energy and 16.79 kWh/d/p of hydropower. If regarding biomass as a primary energy, and assuming 40% being the average efficiency to convert primary energy into electricity, the total power of the seven kinds of renewable energy reserves is about 78.03 kWh/d/p, which is equal to 2.75 times of 28.35 kWh/d/p of national power generation in 2008. If the reserves of 54.93 kWh/d/p estimated from other four kinds of renewable energies that have not technically matured yet are also taken into account, it will result that the reserves of renewable energy in Taiwan can be quite abundant.

Although the results of the assessment point out that Taiwan has abundant renewable energy resources, the four inherent shortcomings – low energy density, high cost of power generation, instability of power supply, and current cost of renewable energy being still higher than that of fossil energy – have to be overcome first, before renewable energy is actually formed as a main component in national energy mix. The measures executed by government to break through these barriers further include the upgrade of the technological level, the formulation of the necessary policies, and the work together from all levels for the overall promotion.

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1. Introduction

Based on Energy Statistics Manual in 2008 published by Bureau of Energy of Ministry of Economic Affairs, the national energy structure in demand side is still mainly comprised of fossil fuels, such as coal and coal products (32.42%), crude oil and petroleum products (49.46%), natural gas (9.42%), *etc.* Produced by burning fossil fuels, greenhouse gases (mainly carbon dioxide) have been identified as the main cause for global climate change, while emissions in Taiwan in 2008, a total of approximately 270 Mt (million tone) of carbon dioxide, accounting for about 1% of global emissions, with annual growth rate of more than 5% over the past 20 years, is really shocking. Renewable energy is considered non- or less-polluting sustainable energy, but the proportion of renewable energy on supply side in Taiwan is still very low, only 0.29% for the usual hydro, and only 0.04% for solar photovoltaic and wind power. In addition, since most of the aforementioned fossil fuels are imported from abroad, and mostly from the political instable countries in the Middle East or Southeast Asia, security of energy supply is a major worry for Taiwan.

To solve above problems, the development of renewable energy may be the necessary measures. In fact, reserves of renewable energies in Taiwan should be quite rich, because there are plenty of remarkable conditions as follows. First of all, Taiwan is located in subtropical area, in which the Tropic of Cancer passes through central Taiwan, so the insolation time is long and the angle of daylight deflection is small, very suitable for the development of solar energy. In addition, there are summer and winter monsoons along the western ring of Pacific Ocean, making Taiwan Strait like a fast wind tunnel. Meanwhile, with the west coast stretching a large bank, Taiwan has a great potential for offshore wind power generation. Particularly, with wind speed up to 7 m/s and above all year round, the area of Penghu is a wind field of high-quality. Potential of biomass energy cannot be underestimated either. Apart from wastes generated from livelihood of people, industry and agriculture, plenty of energy crops can be used for producing biofuels. Particularly, the second generation of biomass crops, such as oil algae and cellulose, would not lead to the food crisis. Because thousands of kilometers of coastal waters and the vast majority of forest land can be used to farm or cultivate these energy crops, there are considerable potential with respect to biomass energy in Taiwan. In the meantime, Taiwan located at the juncture of Eurasian Plate and Philippine Sea Plate is also a part of the Ring of Fire series including the Philippines, Japan, Indonesia and other countries, where geothermal energy has developed in grand occasion, so we can see that the development potential of geothermal energy here in Taiwan should not be taken lightly. High mountain terrain and abundant rainfall (annual average of about 90 billion tons) also provide considerable hydroelectric potential. At last, Taiwan is surrounded by the ocean and is suitable for the development of marine energy. Not far from the east coast, the sea water on the ocean surface is warn, but is ice-cold at the depth of thousands of meters, providing an excellent location for ocean thermal energy conversion. With flow rate of 1 m/s and average width of 100 km, Kuroshio, part of North Pacific circulation, turning north through the Philippines, passing by the eastern coast of Taiwan, finally flowing north steadily throughout the year to Japan, is a huge momentum for Taiwan's ocean energy to develop electricity generation with infinite potential.

In short, based on the assessment results of this paper, there are inherently favorable conditions for Taiwan to develop renewable energy resources. As long as the development is proper, the electricity generated from the renewable energies in this island can reach self-sufficiency in next two or three decades, not only to address national security of energy supply and sustainable management, but it may also bring enormous business opportunities, like, industry of green energy, for Taiwan. Currently, in Taiwan, the installed capacity of renewable energies (including large hydropower, wind power, solar energy, *etc.*) is 5.5 GW in a national proportion of 11.93%, while the correspondingly annual electricity generation is only 7.9 TWh accounted for 3.11% nationally only. Compared to the huge potential assessed by this paper, such a low ratio is out of proportion. Therefore, in addition to the practice of overall examination and revision, we want to urge the government to comprehensively review the feasibility and urgency of developing renewable energy in various levels, such as policy, regulations, incentives, subsidies, promotion and so on, so that Taiwan can have a clean energy under self-sufficient state in the nearest future.

Based on the public data without any new investigation, this paper comprehensively assesses the reserves of seven kinds of renewable energies in Taiwan, including solar energy, wind power, biomass energy, wave energy, tidal energy, geothermal energy, and

hydropower. Essentially, a reasonable and almost realistic assessment should be conformal to two requirements: (1) sufficient and accurate data; (2) assessment logic based on actual situation. Obtained from existing literatures or Web sites of competent authorities, the data adopted by this paper include: the amount of insolation, land areas and sea areas in corporation with the speed distribution of wind, wave and tidal range data, annual rainfall, shallow geothermal data, land information (such as use, area, *etc.*), terrain data, *etc.*, for the entire Taiwan.

Moreover, in general, there are two kinds of assessment methods for renewable energies, namely, "Top-down" and "Bottom-up". The former is typically exampled by MacKay [1], the algorithm of which is to multiply the reserves of energy per unit area by the available land or sea area to obtain the product so-called the "total amount of available reserves". This kind logic of assessment is mostly adopted in evaluating the reserves of renewable energies of an entire country or large area. Apart from considering these two parameters, namely, unit reserve and area, the "Bottom-up" method further considers other factors, like, economic factors (e.g., high cost), environmental factors (e.g., the impact on the environment or ecology), decrees factors (e.g., low prices of oil and electricity, and access barriers, such as the permission of development) and other factors may have triggered the real obstacles. The "Bottom-up" method must estimate the real "exploitable reserves", which are needed by the industry when considering the development of renewable energy resources. Since of these practical obstacles, the "Exploitable reserves" are frequently much lower than "Available reserves," as described in MacKay [1]. As to how much can be developed, it all depends on the wisdom, determination and strength of the government in promoting renewable energy.

Overall, the method of assessment made by this article could be regarded as a "Top-down" approach, because the fundamental logics are all come from the product of "unit reserve" and "usable area". However, for some items of more mature technologies, the practical experience and the data would be taken from those of Taiwan, Europe, the United States and Japan, who have promoted renewable energy for years, in which cases and obviously unfeasible conditions resulted from the factors of economy, environment, decree, *etc.* are excluded, so it can be said that some sprite of "Bottom-up" approach is also adopted in this paper. Since in lack of data, we cannot help use this kind of assessment method based on mixed logics. However, we also take into account a number of known limitations to hope that an overall evaluation of results not only can be "optimistic as far as possible" (from top to bottom), but also can be "actual as close as possible" (from bottom to top).

Thereinafter, six sections (Sections 2–7) will be constructed to describe the detailed assessment of the usable reserves of seven kinds of renewable energies already developable in Taiwan, namely, solar energy, wind power, biomass, wave and tidal energy (combined to one section), geothermal, and hydro. The adopted data are all publicly available information, and the outcomes of assessment are further compared with those of other scholars [1–5] (see Table 6). Meanwhile, the similarities and differences are collated and illustrated by tables (see Table 7). Finally, in Section 9 of the conclusions, we also assess the target reserves of the renewable energy of immature technology but of enormous potential: the second generation of biomass energy, deep geothermal power generation, Kuroshio power generation, ocean thermal energy conversion, and note the technical bottleneck of the likely trends or future developments for these items as well. We also collate the reserves of renewable energies of the major countries or regions around the world to highlight that Taiwan has abundant reserves of renewable energy (see Table 9). In this paper, after the total reserves for each item is estimated, it will be divided by the number of Taiwanese population and the number of days a year to become an estimation unit in "daily reserves per capita" (kWh/d/p).

2. Solar energy

Taiwan, a medium island in subtropical area, geographically located between east longitude 120–121° and north latitude 22–25°, is very in favor of the development of solar energy, due to the benefits of long duration of insolation and small angle of daylight deflection. Solar energy not only can improve security of energy supply, but also can immediately relieve the peak load of electricity. In Taiwan, during daytime of summer, the air conditioning consumes a large amount of electricity, which can be supplied by PV facility powered by intensive solar radiation in time. While natural conditions are good, land conditions are very inadequate for the installation of solar equipment in Taiwan. Based on statistical data [6] of Ministry of the Interior in August 2009, the total population in Taiwan is about 23 million, while the land area is approximately 36,000 km^2, resulting in that the land area per capita is 1560 m^2/p. Second only to Bangladesh, the population density of Taiwan is second highest in the world. Worse still, 2/3 of the island land is mountain area, only 1/3 of land suitable for housing, which is concentrated in the south-west coast, making Taiwan have great limitation in the area of land to install solar power facilities.

Regarding the mean estimates of the amount of insolation in Taiwan, first of all, under the provisions of land areas of cities and counties by the Ministry of the Interior [7] and the regional annual average amount of insolation by the Central Weather Bureau [8], this paper adds the regional product of both the area and the amount of insolation for hundreds of national land areas. Then, the sum is divided by the total country area; as a result, the average amount of insolation per unit area per year in Taiwan is 1130 kWh/m^2 y = 129 W/m^2 (the British average solar intensity referred by MacKay [1] was 100 W/m^2).

"Area of available land" constitutes the main constraint of the development of solar energy in Taiwan. This article assumes only two locations suitable for the installation of solar energy equipment, namely, the roof of building and the land of open space. With respect to solar equipments, this paper only considers solar water heating systems and solar electric power systems, the former using collector to absorb solar radiation to produce hot water, while the latter uses photovoltaic panels to convert sunlight into electricity, both of which can be installed on the roof of building or independently built on the ground.

2.1. The potential of installations on the roof of building

This subsection will assess the developable potential of solar water heating systems and solar photovoltaic systems to be constructed on the roof of building. The process, data and formula for evaluating the assessment are described in Table 1, in which the relevant data are mostly adopted from those in Ref. [2].

The overall results of estimation are as follows:

- Solar water heating systems: As shown in Table 1, the total potential of installation of solar water heaters is 17.8 million m^2 (i.e., the area of total collectors potentially installed on the roof), while the equivalently generated energy (per person per day) is 1.19 kWh/d/p. For comparison, the national actual total installation area at the end of 2008 is 1.78 million m^2, representing a residential penetration rate of only 5%, so there is still substantial room for growth.
  - Solar PV systems: As shown in Table 1, the potential of electricity generation estimated by this paper for the solar photovoltaic system (in terms of the building sector in Taiwan) is 65 TWh/y (or 7.74 kWh/d/p). The corresponding value in literature [2] is 51 TWh/y, which is 22% lower than this article's. The main reason causing this difference is the adoption of amount of insolation. Taking the case of Tainan

Table 1
Assessment of the installation potential of solar equipment in the building sector of Taiwan, including the evaluating process, parameter, formula and data.

Process	Parameter	Formula	Data
1	Taiwanese mean construction coverage ratio		60%
2	Taiwanese permitted area		$2000\,km^2$ [9]
3	Taiwanese construction area	Permitted area (2)[a] × construction coverage ratio (1)	$1200\,km^2$
4	Floor area per capita	The population of Taiwan is about 23 million.	$36.3\,m^2/p$ [10]
5	Residential density	Taiwanese population (23 million)/Taiwanese construction area (3)	$19{,}200\,p/km^2$
6	Floor area ratio		135% [2]
7	Roof area available for setting up solar energy systems	Construction area (3) × 50%. Assume the utilization ratio being only half	$600\,km^2$
8	Floor area covered by roof where solar energy system is set up	Roof area available for setting up solar energy systems (7) × floor area ratio (6)	$810\,km^2$
9	Residential population capable of being served with solar water heating system	Floor area covered by roof where solar energy system is set up (8)/floor area per capita (4)	22.3×10^6
10	Total installation area of solar water heating system	For a general Taiwanese family of five people, $4\,m^2$ is supposed to be the required installation area of solar water heating system.	$17.8\,km^2$
11	Total roof area available for the installation of solar PV system	Roof area available for setting up solar energy systems (7) – total installation area of solar water heating system (10)	$582.2\,km^2$
12	Value of heat generated from solar water heating systems	Total installation area of solar water heating system (10) × the amount of insolation ($1130\,kWh/m^2$-y) × thermal efficiency of solar water heating system (50%)	10 TWh/y = 1.19 kWh kWh/d/p
13	Amount of electricity generated from solar PV system	Total roof area available for the installation of solar PV system (11) × the amount of insolation ($1130\,kWh/m^2$-y) × power generation efficiency of solar PV system (10%)	65 TWh/y = 7.74 kWh/d/p

[a] Representing data of step numberSof process.

County as example, the amount of insolation adopted by literature [2] is $371.79\,kWh/m^2/y$, while this paper still uses the pool value of $1130\,kWh/m^2/y$. In addition, the conversion efficiency of PV panel used in this paper is 10%, while the literature [2] uses 20% for the efficiency of PV panel and the correction factor of 0.75 mainly to consider the influences of architecture and environment, so its final value of conversion efficiency is 15%.

2.2. The potential of installations on open space: PV Farm

If large solar photovoltaic systems would be built in Taiwan, not only their equipment costs are still much higher than the fossil energy equipment's, but also a major obstacle is incurred from the costs of a large area of land required for the installation of PV farms (or large stand-alone systems). Therefore, in order to obtain operating profits and value, the development of PV farm must be under the premise of no land cost. Accordingly, this subsection proposes following three possible options, which can be implemented to build a large number of PV farms: (A) the utilization of public marginal land accounted for 1% of the land in Taiwan; (B) the land use of old industrial zone; (C) land reclamation.

(A) If it is assumed that 1% of all land of Taiwan (for example, the common developable marginal land) can be used to install PV farms, under the annual conversion efficiency of 10%, the power generation volume would be as follows.

$$3.6 \times 10^{10}\,m^2 \times 1\% \times 1130\,kWh/m^2/y \times 10\% = 40.7\,TWh/y = 4.84\,kWh/d/p \quad (2.1)$$

There are many ways to acquire this 1% of land, such as

- The open space along both sides of highways: the total length of national highways and fast roads is about 900 km. The adoptable portion is about 70% by deducting the areas of interchange, toll station roadside, tunnels, steep road bridges and other parts unable to set up PV panels. Additionally, hypothetic width for laying PV panel along one side of the highway is 5 m (total of 10 m on both sides), so the total usable area would be as follows:

$$900\,km \times 0.010\,km \times 70\% = 6.3\,km^2 \quad (2.2)$$

- The open space along both sides of railways: the total length of High Speed Rail and Taiwan Railway is about 1450 km. It is supposed that the width along a railway side to be laid PV panels either on ground or elevated is 3 m (total of 6 m on both sides). Also, it is assumed that the special sections accounted for 30% cannot be laid PV panels, so the total available area will be as follows:

$$1450\,km \times 0.006\,km \times 70\% = 6.09\,km^2 \quad (2.3)$$

The combination area of the two options is $12.12\,km^2$, accounting for about 0.034% of the national land area of $36{,}000\,km^2$. There is also sporadic availability of other public lands, such as car parks, parks, playgrounds, squares, military uses reserves, river or riverside, *etc*. But to make the size of installation accounted for 1% of the national land area, there is still a great effort and flexible strategy.

(B) In Taiwan, the aged industrial area is accounted for approximately 75% of all industrial areas, that is, an area of $280\,km^2$. If it is assumed that all old industrial area are used to install PV farm, at 10% conversion efficiency, the available electricity generation with respect to this aspect will be as follows.

$$2.8 \times 10^8\,m^2 \times 10\% \times 1130\,kWh/m^2/y = 31.6\,TWh/y = 3.77\,kWh/d/p \quad (2.4)$$

In recent years, many traditional industries in Taiwan have moved to mainland China or Southeast Asia, so the land of many industrial areas has been abandoned. Therefore, the proposal of this article – 75% of the land of industrial area is used for the installation of PV farm – should be feasible.

(C) Taiwan is a crowded and space-limited island. The concept of "land reclamation" [5] can increase the reserves of solar power.

Table 2
Estimated reserves of solar energies for entire Taiwan (unit: kWh/d/p).

	On roof of building	Large stand-alone system			Total
		On public land (1% of national land)	On old industrial areas	On reclamation land	
Solar thermal	1.19	–	–	–	1.19
Solar PV	7.74	4.84	3.77	6.73	23.08
Total reserves	8.93	4.84	3.77	6.73	24.27

If it is assumed that waters of depths within 20 m are used for land reclamation, then there will be open space of 1000 km^2. It is assumed that 50% of the reclamation land is to build PV farm and the conversion efficiency of PV panel is 10%, then it can obtain additional PV reserves calculated as follows:

$$1 \times 10^2\,\mathrm{m}^2 \times 50\% \times 1130\,\mathrm{kWh/m^2\,y} \times 10\% = 56.5\,\mathrm{TWh/y} = 6.73\,\mathrm{kWh/d/p} \quad (2.5)$$

For the sea of depth less than 20 m, reclamation land of 1000 km^2 can be made. The required 1 billion m^3 debris can be supplied by the siltation of about 1.2 billion m^3 of 11 south-central rivers and by the sedimentation amount of 300 million m^3 of 40 reservoirs. If 50 km^2 of land reclamation is accomplished every year (over the past 50 years, average speed of Japan is 30 km^2), then it will take 20 years to complete the land reclamation of 1000 km^2. Using reclamation land to install PV panels will not affect of the reserves assessment of offshore wind in Section 3, because wind turbines can be erected on new-created land without too much influence on the installation of PV panels, under the assumption of "utilization of 50% only".

Recently, the Taiwanese government has also intended to open the lands of Taiwan Sugar Company to set up PV farm, but for the purpose of growing biomass crops, all of these sites are defined as "waste agricultural land" in this article and therefore cannot be repeated in this consideration.

2.3. Total reserves of solar energy

By the overall integration of the above types of data, as organized in Table 2, the total available potential of solar energy (including solar thermal energy and solar PV energy) in Taiwan is about 24.27 kWh/d/p, so it can be said that the solar energy in Taiwan is quite abundant.

In Taiwan, solar collectors or PV panels are mostly installed with an inclination angle of 23.5° (with respect to ground or flat roof), because the Tropic of Cancer (north latitude 23.5°) just passes through the center of Taiwan. But since the incidence angle of sunlight still changes over the time of a day, in theory, generation efficiency will change correspondingly to reduce the overall power generation.

3. Wind power

According to the investigation of NASA [11], the average density of wind power exceeds 750 W/m^2 in the coastal areas of Taiwan, so the conditions of the development of wind power in Taiwan are fairly favorable. Although wind power has the problem of poor stability, with the progress of storage technologies, the related issues are expected to be addressed one by one.

3.1. Wind energy estimates program

In Taiwan, due to the lack of detailed information of wind farms, several parameters required to estimate the wind energy are still unknown. To compensate this deficiency, this paper uses two different ways in calculating the wind power.

Case 1. Estimation by adopting "the cube of the average wind speed"

Mackay [1] uses the cube of the average wind speed to estimate the wind power in the UK. If the information of wind power is insufficient, such as when the distribution factor of the wind speed (shape factor) is unknown, then it needs to estimate the wind power by "the cube of the average wind speed". Accordingly, the total output of electricity (kWh) of wind farm per year can be estimated by Eq. (3.1).

$$E_1\,(\mathrm{kWh}) = \sum N \times 2000\,(\mathrm{kWh/h}) \times C_{A1} \times 24\,(\mathrm{h/d}) \times 365\,(\mathrm{d}) \quad (3.1)$$

where N is the number of wind turbine for a specific level of wind speed, 2000 is derived from the electricity generation per hour of a wind turbine of 2 MW, C_{A1} is the capacity factor and defined as $(v_a/v_{rated})^3$, where v_a is the average wind speed for a certain level of wind speed and v_{rated} is the rated wind speed (assumed to be 12 m/s). The other conditions of wind turbine are defined as follows: the cut-in speed is 4 m/s, the cut-off speed is 25 m/s, the power conversion coefficient is 0.4, and the rotor diameter of a horizontal wind turbine of 2 MW is about 80 m.

Case 2. Estimation by adopting "the mean of the cubic wind speed"

In the previous case, the adoption of "the cube of the average wind speed" will underestimate the wind power to some extent. In the present case, it is assumed that the variation of wind speed is a Weibull Distribution. Please refer to Eq. (3.2).

$$f(v) = (k/S_c)(v/S_c)^{(k-1)}\exp\{-(v/S_c)^k\} \quad (3.2)$$

where k is the distribution factor (assumed with a number of 2), S_c is the scale factor, and v is the wind speed. According to the wind speed of each level, the corresponding scale factor can be calculated, and then the total generation output can be further calculated from Eq. (3.3).

$$E_2\,(\mathrm{kWh}) = \sum N \times 2000\,(\mathrm{kWh/h}) \times C_{A2} \times 24\,(\mathrm{h/d}) \times 365\,(\mathrm{d}) \quad (3.3)$$

where

$$C_{A2} = \int \left(\frac{v}{v_{rated}}\right)^3 f(v)dv \quad (3.4)$$

where v is the wind speed, and C_{A2} can be derived from numerical integration. In Eq. (3.4), the integral upper and lower limits are respectively taken as 0 and 30 m/s. Regarding the average wind speed in the level of 8–9 m/s explored in this article, the probability of the wind speed above 30 m/s is almost 0, so the ceiling of 30 m/s should be consistent with the actual situation. If the variation of wind speed belongs to a Weibull Distribution (most of stable wind

power would be), the results calculated by Case 2 should be better able to meet the output energy of an actual wind turbine [12].

3.2. Terrestrial wind energy reserves

According to the estimate of literature [13], at least thousands of wind turbines (each with capacity of 2 MW) can be installed on the land of Taiwan, where the wind speed is above 4 m/s. However, if further considering noise, safety, acceptance of residents and other factors, the number of wind turbine actually set up may not so much. In order to actually assess the potential of wind energy in Taiwan, the estimations of this paper are made from different points of view.

(1) The installation of large wind turbine with horizontal axis along coastal areas.

Here, the coastal areas for the installation of large wind turbine (i.e., with a capacity of 2 MW and horizontal axis) are conformal to the following three conditions: (1) coastal areas (excluding conservation areas [14]), (2) off the road or building 250 m or more and (3) the average wind speed in the height of 50 m is above 4 m/s. We adopt the data from Google Map [15] and take three or six times of rotor diameter [3] as the interspacing distance between two neighboring turbines (i.e., 240 or 480 m). The calculated results show that the coastal areas of Taiwan and Penghu can be installed large wind turbines of a total capacity over 1200 MW. If calculated by the equation of Case 1, the total electricity generation per year will be about 1400 GWh or 0.17 kWh/d/p. If calculated by the equation of Case 2, the result will be approximately 2500 GWh or 0.30 kWh/d/p.

In addition to the coastal areas, of course, there are many open areas in the inland capable of being installed with large wind turbine. However, in the inland, influenced by erected terrain or objects, the wind speed becomes weakened or unstable. At the same time, the expansive land in Taiwan significantly increases the cost of power generation, lowers the feasibility, and increases the operational risk, so in this article there is no consideration for the inland area to be installed large wind turbines.

(2) The roof of buildings erected small wind turbine with vertical axis.

Small wind turbine with vertical axis is quieter and is more easily implemented on the roofs of high-rising residential-, public-, commercial- and other-buildings. Since the small wind turbine with vertical axis cannot control the ratio of lift and drag to a maximum, so the power conversion coefficient is only about 0.3. We assume that the small wind turbine with vertical axis has a rated power of 2 kW, a rated wind speed of 12 m/s, and a rotor wind area of approximate 6.3 m^2 (rotor diameter is about 2.5 m). We still calculate the number of small wind turbine set up according to the interspacing distance of three or six times of the rotor diameter (i.e., 7.5 or 15 m). The wind condition considered here is that the wind speed is greater than 4 m/s in the height of 10 m from the roof of building. The total area on the roof of building (about 75 km^2) conformal to this condition will be erected small wind turbine. In addition, we also consider the open space approximately with area of 150 km^2, wind speed of more than 4 m/s in the height of 5 m to be installed small wind turbine. The total installation capacity of both locations (i.e., roof and open space) is up to about 4000 MW. If calculated by the equation of Case 1, the total electricity generation per year is about 2570 GWh or 0.31 kWh/d/p. If calculated by the equation of Case 2, the total electricity generation is approximately 5200 GWh or 0.62 kWh/d/p.

3.3. Offshore wind energy

With fewer and fewer areas available in land, the development of offshore wind farm on the sea is inevitable. Setting up offshore wind farm on the sea can keep the people from the affects of noise or visual impact and avoid the high land cost. At the same time, due to fewer obstructions, the wind on the sea surface has higher speed than the inland area's, in addition to smooth airflow and stability, so the overall availability of offshore wind farm is higher than that of terrestrial wind farm. But, since involving marine works, the erection cost of the former is higher than that of the latter. The cost of constructing offshore wind turbine is proportional with the sea depth [16]. In waters less than 30 m depth, pile- or gravity-typed base can be used as a wind turbine platform to reduce costs; in 30–60 m deep waters, the three-legged truss is generally used as the pile or foundation of the wind turbine; while in the water depth of 60 m and above, a floating platform should be used as the wind turbine base. Although the United States has developed a technology of deep-sea floating platforms for offshore wind turbine [17], making wind turbine able to be installed in water area with depths of more than 200 m, there is still no actual measurement data seen in the open literatures yet.

In this paper, we assess the reserves of offshore wind energy in the sea area with water depth less than 40 m (due to the considerations of the engineering feasibility and cost-effectiveness). The locations of estimation are divided into three areas: area with water depth of 20 m or less; area with water depth within 20–30 m; and area with water depth within 30–40 m [18,19]. The wind speed condition of above chosen areas is 5 m/s and above [13]. After excluding the conservation area and considering both the territorial sea range of 12 nautical mile [20] and the eastern scope from the center line of Taiwan Strait [21], the areas conformal to the above conditions will be erected large wind turbines, each with a capacity of 2 MW and interspaced with a distance of three or six times of the rotor diameter (i.e., 240 or 480 m). Estimation results are described below.

- Wind energy for the water depth less than 20 m: the number of wind turbines potentially set up in this sea area is about 8300 with a total installation capacity of 16.6 GW. If calculated by the equation of Case 1, the total electricity generation per year is about 28.9 TWh or 3.44 kWh/d/p. If calculated by the equation of Case 2, the total electricity generation is approximately 41.2 TWh or 4.91 kWh/d/p.
- Wind energy for the water depth within 20–30 m: the number of wind turbines potentially set up in this sea area is around 10,500 with a total installation capacity of 21 GW. If calculated by the equation of Case 1, the annual total electricity generation is roughly 46.4 TWh or 5.52 kWh/d/p. If calculated by the equation of Case 2, the total electricity generation per year is substantially 70.1 TWh or 8.35 kWh/d/p.
- Wind energy for the water depth between 30 and 40 m: the number of wind turbines potentially set up in this area is about 17,950 with a total installation capacity of 35.9 GW. If calculated by the equation of Case 1, the total electricity generation per year is about 84.5 TWh or 10.07 kWh/d/p. If calculated by the equation of Case 2, the total electricity generation per year is about 126.3 TWh or 15.04 kWh/d/p.
- Total wind energy reserves for three kinds of water depths: the wind energy of the three different regions on the sea is summed up as the total reserves of offshore wind energy in Taiwan. If calculated by the equation of Case 1, the total electricity generation per year is about 159.8 TWh or 19.03 kWh/d/p. If calculated by the equation of Case 2, the total electricity generation per year is about 243.3 TWh or 28.98 kWh/d/p.

3.4. Compared with the previous findings

With respect to the estimated reserves of offshore wind energy in Taiwan, Yang and Yu [3] estimated that the total installation capacity is 110 GW close to 100 GW estimated by Lin and Chen [5]. The main sources of difference between the estimate of this paper (i.e., 73.5 GW) and the literatures' [3,5] are as follows.

First of all, Yang and Yu [3] considered that the rotor diameter of the wind turbine of 2 MW is 66 m, while in this paper we consider that the rotor diameter of the wind turbine of 2 MW is 80 m. Therefore, within a same area, the number of set up wind turbines estimated by Yang and Yu [3] is about 1.47 times of this article's.

Secondly, the rated wind speed considered by Yang and Yu [3] is 17 m/s, while the rated wind speed considered by this paper is 12 m/s, making the electricity generation of each wind turbine estimated by Yang and Yu [3] be four-fifth of this paper's.

These two factors have led to the result that the potential estimated by this paper is about 16% less than that of Yang and Yu [3]. In addition, other factors adopted during calculation, such as the difference of available offshore area and the error of wind power data, also contribute to the differences between these two estimates.

Furthermore, other two existing studies also made different estimates respectively, such as 2 GW of the literature [22] and 1.2 GW of the literature [23]. The results of these two studies fall far short of this paper's. The reasons should be the further considerations of other factors, such as engineering, geology, economy and operation. However, there is lack of detailed explanation in these two references [22,23].

3.5. The total reserves of wind energy

To sum up, the total potential of installation capacity of wind power in both areas of land and sea in Taiwan is at least 80 GW. Based on the algorithm of Case 1, the electricity generation per year is about 165 TWh (or 19.65 kWh/d/p). On the other hand, according to the algorithm of Case 2, the electricity generation per year is about 254 TWh, which is not far off 238.33 TWh [24], the total electricity generated by Taipower in 2008. Although wind still cannot provide stable power under current technology, with the advances of nano-materials technology to develop energy storage device [25] in small volume and with high energy density, the stability of wind power can be improved significantly in the future.

4. Biomass energy

In addition to wastes of industry, agriculture, forestry, urban and others, there is a wide range of biomass, and so are the biomass crops of first generation, such as the sugar cane for ethanol and the rapeseed for biodiesel. The population of Taiwan is so dense that the development potential of biomass cannot be put on par with those of large countries, such as Brazil, China and the United States. However, in addition to the global turmoil of energy saving and carbon reduction at present, under the predicament of a large number of abandoned farmland in Taiwan, the development of biomass not only can significantly enhance the security of energy supply and revitalize the agricultural economy, but also can boost the technology of energy industry. The benefits are so rich that it is worthy of careful assessment and planning.

In this article, to assess the potential reserves, the biomass energy is divided into three categories, for example, biomass crops of first generation, urban waste, and wastes of agriculture and forestry. The relevant estimates are detailed as follows.

4.1. Biomass crops of first generation

When estimating the overall reserves of biomass crops, there are two main factors needed to be considered, namely, the available planting area and the energy density of biomass crops. With existing data, we respectively explain the estimates of these two factors as follows.

- Area can be planted: According to the statistics, used by Li and Yu [4], also available in Geographic Information System of Construction and Planning Agency, the total agricultural area can be used in Taiwan is approximately 5150 km^2. The cultivable area of energy crops (about 2580 km^2) is supposedly over 50% of the total agricultural area. This assumption is consistent with the actual planting area of the current requirements in Taiwan, because in 2004 the fallow area in Taiwan had reached 2300 km^2. The rest of the agricultural area can be used for future purposes such as the expansion of food production, crops planting, aquaculture and fisheries. This kind of land combination should be reasonable.
- Energy density: In Fig. 6.11 of MacKay [1], the statistics of the energy density of biomass crops per unit area (W/m^2) is illustrated. Accordingly, 2% would be the highest solar energy conversion efficiency in the plants for the production of carbohydrates. In this article, the mean value of aforementioned statistics – 0.5 W/m^2 – is taken as the representation of energy density of all kinds of energy crops in Taiwan. Furthermore, it is supposed that 67% is the efficiency to convert carbohydrate of plants into transportation fuel (i.e., there is 33% energy loss during the conversion process) [1], then the energy supply potential from biomass fuel per year in Taiwan will be as follows.

$$0.5\,\mathrm{W/m^2} \times 2.58 \times 10^9\,\mathrm{m^2} \times 8760\,\mathrm{h/y} \times 67\% = 0.90\,\mathrm{kWh/d/p} \tag{4.1}$$

4.2. Urban waste

In Taiwan, the garbage from people daily lives is about 1.1 kg per day per person, or 9.23×10^6 ton per year for the entire country. The current waste disposal methods are various, including recycling, incineration, sanitary landfill, general burial, and stacking. In general, the composition proportions of garbage in Taiwan are as follows: (1) over 30% is paper, which can be handled by recycling manner; (2) 30% is kitchen waste, which can be processed by digestion tank fermentation, and the resulting biogas can be used as fuel; and (3) the remaining 40% are other types of wastes, and when dealt through incineration process, only 4.91% of burned wastes can be used as part of the fuel for energy generation. Over the past two decades, under the support by government policies, 21 large-scale garbage incineration plants are promoted and constructed smoothly. The waste disposal capacity is 21,900 ton per day, about half of which have been incinerated. With a total power generation capacity of 450 MW [26], the generated waste heat can be used to generate electricity of 120 GWh/y, which is equivalent to 44% of the total power generation of three nuclear power plants in 2008 [27]. It is estimated that the net power generation efficiency is 2.5%.

The following are estimates of energy generated from various types of garbage.

- Incinerated garbage: The estimate of heat value of garbage incineration is as follows.

$$9.23 \times 10^6\ \text{ton/y} \times 40\% \times 4.91\% \times 15.7\ \text{GJ/ton}\ (\text{RDF calorific value}) = 0.09\ \text{kWh/d/p} \quad (4.2)$$

- Processed kitchen waste: 10 kg of processed kitchen waste can produce 1 m^3 of biogas with heat value equivalent to natural gas of 0.75 m^3, and burning 1 m^3 of natural gas will generate heat of 0.04 GJ, so every ton of kitchen waste can produce heat of 3 GJ [4]. The equation is as follows.

$$\text{Total kitchen residue} \times 3\ \text{GJ/ton}\ (\text{calorific value of kitchen residue}) = 9.23 \times 10^6\ \text{ton/y} \times 30\% \times 3\ \text{GJ/ton} = 0.27\ \text{kWh/d/p} \quad (4.3)$$

Comparing (4.2) and (4.3), the total amount of energy generated from processed kitchen waste is triple of that of incinerated garbage, showing that the recycle of kitchen waste should not be ignored in our daily lives.

4.3. Wastes of agriculture and forestry [4]

Wastes of agriculture and forestry are mostly comprised of residues of straw and wood. Gathered statistically by the Environmental Protection Agency, the annual output of wastes from agriculture and forestry is 6.34×10^6 ton. If using RDF technology [28] to process the wastes, the obtained overall thermal energy is 27.6 TWh/y, and the calculation equation is as follows.

$$6.34 \times 10^6\ \text{ton/y} \times 15.7\ \text{GJ/ton}\ (\text{RDF calorific value}) = 3.29\ \text{kWh/d/p} \quad (4.4)$$

4.4. Total reserves of biomass energy

As shown in Table 3, the total reserves of biomass energy can be obtained by orderly aggregating the energies from the three categories: first generation of biomass crops, urban waste, and wastes of agriculture and forestry.

As known in Table 3, the reserves of biomass in Taiwan can provide Taiwanese with energy of 4.55 kWh/d/p, equivalent to the electric power of 1.82 kWh/d/p. Among these three kinds of biomass, the wastes of agriculture and forestry possess the highest amount of thermal energy, but also have relatively low cost, unlike biomass crops needing a huge cultivation land. However, in order to be benefitted from economic effectiveness, the most important prerequisite is that the power plant of high performance should be located in the vicinity of waste collection field, where the wastes come from industry, agriculture, forestry or urban.

Table 3
Assessment of the total reserves of biomass energy in Taiwan.

	Reserves (kWh/d/p)	Equivalent power (kWh/d/p)
Biomass crops	0.90	0.360
Urban waste	0.36	0.144
Wastes of agriculture and forestry	3.29	1.316
Total potential	4.55	1.820

5. Ocean energy

Taiwan is surrounded by sea and has coastline of 1500 km or more [29]. Therefore, lots of wave energy or tidal energy may be reserved. This section assesses the reserves of these two kinds of energies.

5.1. Wave energy

Based on statistics [29] of Water Resources Agency of Ministry of Economic Affairs, the coastline of main island of Taiwan is about 1134 km and further up to 1566 km if including outlying islands. The coastline is still more than 1000 km, even after deducting the protected areas. As long as the wave energy densities in these waters are known, the wave energy potential then can be calculated. Based on the data along Taiwan coasts [30], provided by Central Weather Bureau in 2008, such as the wave height and period all year around, the numerical values regarding the wave speed C and wave length λ can be calculated from Eqs. (5.1) and (5.2), respectively.

$$\lambda = \frac{g}{2\pi} T^2 \tanh \frac{2\pi d}{\lambda} \quad (5.1)$$

$$C = \frac{\lambda}{T} \quad (5.2)$$

where λ is wavelength, T is period, g is acceleration of gravity (9.8 m/s^2), and d is water depth. According to the distribution data [18,19] of water depth in local waters, the means of above parameters can be obtained individually. And then based on Eq. (5.3) [31], the wave energy density per unit width of wave (W/m) can be calculated.

$$P_w = \left(\frac{1}{8}\rho g H^2\right) C \left\{\frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)\right\} \quad (5.3)$$

where P_w is the power transmitted by wave per unit width of wave (W/m), ρ is the seawater density (1030 kg/m^3), ($k = 2\pi/\lambda$) is the wave number and H is the wave height. The average energy flux (W/s), at a cycle time, from sea floor to wave surface and in the direction of wave, can also be converted from Eq. (5.3).

Currently, the information of wave along the coasts of Taiwan can only be obtained from the results monitored by few sporadic observation stations in the long-term, such as Hsinchu, Mai Liao, Oluanpi, Longdong, Suao, Hualien, Cheng Kung, Mirs Bay, Chiku, and Penghu. This article divides the all coasts into five waters: east, south, west, north and Penghu, and then based on the limited observational data in these waters, the average wave height and period are estimated. Next, according to various water depths, the average wavelength and wave speed are calculated. Finally, the power transmitted by wave per unit length can be obtained. This article assumes that the variation of wave height (H) is a Weibull Distribution (Eq. (5.4)) with a distribution factor (k_1) of two. Thereby, according to average wave height, the corresponding scale factor (S_1) can be calculated. Finally, based on Eq. (5.5), the wave energy transmission power (in unit of W) can be estimated.

$$f_1(H) = \left(\frac{k_1}{S_{c1}}\right)\left(\frac{H}{S_{c1}}\right)^{(k_1-1)} \exp\left\{-\left(\frac{H/}{S_{c1}}\right)^{k_1}\right\} \quad (5.4)$$

where k_1 is the distribution factor, S_{c1} is the scale factor, and H is the wave height.

$$P_{wt} = \sum \frac{1}{8}\rho g\left(\int f_1(H) H^2 dH\right) C \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right) L \quad (5.5)$$

where L is the coastline length of each area (excluding the conservation areas [14]). The integral upper and lower limits are taken 0 and 5 m/s, respectively. Since the maximum average wave height is 1.32 m (in Penghu), the probability of wave height of more than 5 m has been close to zero, so the ceiling should be taken 5 m, which is in line with the actual situation. The results show that after excluding the reserves in protected areas, the total power of the sea wave is about 8800 MW, and the total energy generated in 1 day is about 210 GWh or 9.13 kWh/d/p.

To be converted into electricity, the aforementioned energy requires appropriate machinery. If Pelamis is considered as the machinery to convert wave energy into electricity, in accordance with its operating curve [32], it is known that for waves with period less than 5, the wave height of start must be greater than 1 m, and for waves with period between 5 and 13, the wave height of start must be greater than 0.5 m. Similarly to the distribution of the above calculation, if a Weibull Distribution is adopted, then the total available power is 8200 MW. If the generation efficiency of Pelamis is supposed 50% [1], then the maximal electricity generated in 1 day is 100 GWh or 4.35 kWh/d/p.

5.2. Tidal energy

The coasts in main island of Taiwan are mostly flat and sandy (e.g., the western coast) or rocky and straight (e.g., the eastern coast). In lack of the bay like Severn Estuary in the UK, it is not easy to build tidal pools in Taiwan. In the meantime, the areas of abandoned or less-used harbors are too small to reserve large potential of tidal energy [33]. Although the tide in Penghu is not much [30] (its average tide is 1.96 m), if Harbor Magong, a bay of rocky coast, is built dam at the exit to intercept tide, then the reserve of tidal energy might have sufficient potential to explore, due to economic benefit. The detailed assessment is as follows.

The calculation of tidal energy is available in Eq. (5.6).

$$P_t = \left(\frac{1}{2}\rho g H_t^2 A_t\right)/t \tag{5.6}$$

where H_t is the tidal difference, A_t is the area of tide accommodated by reservoir, and t is the upping (or lowing) time of tide (about 6 h or 21,600 s in Penghu).

According to the calculation of Eq. (5.6), the tidal power provided by Harbor Magong during a high tide or low tide is about 9 MW, where H_t is 1.958 m and A_t is 10 km^2, and then the total energy reserved in 1 day is about 0.22 GWh. If the conversion efficiency of tidal generator is 0.9 (which is the highest efficiency only owned by hydro-turbine of dam type) [1], then the available electricity generated in 1 day is 0.20 GWh.

If the tidal reservoir area further includes the periphery of Penghu Bay (i.e., Penghu Bay, Harbor Magong and Inner Harbor Magong), the total area is expanded to about 70 km^2. The generated power can be increased to 62 MW during a high tide or low tide, and the produced energy in 1 day is up to 1.49 GWh. If the mechanical power conversion efficiency is assumed 0.9, then the electricity generated in 1 day is 1.34 GWh or 0.06 kWh/d/p.

In addition to Penghu, Kinmen and Matsu also have potential to develop tidal energy. According to the analysis of literature [30], the tides of Kinmen and Matsu are about 3.8 and 4.3 m, respectively. If tidal dams are built at southern outside of Liaoluo Bay of Kinmen and Beigan of Matsu, the areas of tide accommodated in the reservoirs are approximately 40 and 10 km^2, respectively. And then from Eq. (5.6), the tidal power reserved in Kinmen and Matsu are approximately 131 and 43 MW, and the energies produced in 1 day are about 3.14 and 1.03 GWh. If the mechanical power conversion efficiency is supposed 0.9, then the electricity generated in 1 day are 2.83 and 0.93 GWh, or 0.12 and 0.04 kWh/d/p, respectively.

To sum up the foregoing analyses, the total power reserved in above-mentioned three tidal waters in outer islands of Taiwan is approximately 240 MW. The totally largest energy generated in 1 day is approximately 5.76 GWh. If the mechanical power conversion efficiency is supposed 0.9, then the greatest sum of electricity produced in 1 day is 5.10 GWh or 0.22 kWh/d/p.

6. Geothermal energy

In the geological point of view, Taiwan is located on orogenic collision belt between Philippine Sea Plate and Eurasian Plate, so the geology is easy to squeeze and collide, making the occurrence of earthquake be particularly frequent. Meanwhile, the formation is also prone to faults and folds, so that rock layers are constantly uplifted and broken. Furthermore, since rock is a material of low thermal conductivity, heat dissipation is not easy. With the constant uplift of formation and geothermal accumulation in the long term, there is high geothermal gradient resulted in the area of Central Mountain Range. Additionally, in northern Taiwan and eastern islands, large-scale volcanic activity had been occurred; at present, although the volcanic activity is suspended, the hot magma is still reserved under volcano.

In the view point of climate, since Taiwan is located at the edge of West Pacific Ocean, with the influences of northeast monsoon in winter and the south-west monsoon and typhoons in summer, the average rainfall in 1 year is 2500 mm and above. After rain falls down to ground, water flows along fissures or broken rock into ground and is heated by geothermal gradient or hot magma, resulting in rich geothermal resources, so hot spring is an important feature of a geothermal system. From the present geothermal development of grand occasion in other neighboring countries with the same geological and climatic conditions, such as the Philippines, Japan and Indonesia, we can see that the development potential of geothermal in Taiwan should not be underestimated.

The only two volcanic geothermal systems in Taiwan are the geothermal areas at northern Mt. Datun and Turtle Island off the coast of Ilan, while other geothermal areas are water-based and non-volcanic geothermal systems, mostly located in the metamorphic rocks areas of Central Mountains and a few located in the sedimentary rocks area of western foothills belt. According to the long-term research [34] of ITRI commissioned by Ministry of Economic Affairs, the results indicate that there are a total of 26 geothermal resources in Taiwan, such as the geothermal areas of Mt. Tatun, Chinsuei, Kinglun, Lushan, Tuchang, Chihpen and so on, all of which are shallow geothermal, but also the focus of this estimate. Shallow geothermal areas are mostly water-based geothermal systems with non-volcanic nature, and the only volcanic geothermal system is the geothermal area in Mt. Tatun. Mt. Tatun is the geothermal area with largest potential, but unfortunately the corrosion problems existing in produced acidic water are yet to be resolved, so its development has been temporarily stopped. The scales of non-volcanic and water-based geothermal areas are small, each reserving a maximum potential of only about a few million watts, suitable for the development of small and medium scales. Apart from the local power supply of self-use of industry, the geothermal is still available for the direct uses of agriculture, commerce and general resident and for the multi-target applications such as the development of tourism.

Based on the long-term survey data [35] of ITRI, we organize the energy reserves of the above six shallow geothermal areas, as listed in Table 4. Since the detailed data required in the analysis of geothermal reserves are unavailable (e.g., temperature gradient of formation, distribution of rock geology and groundwater hydrolo-

Table 4
List of installation potential of geothermal power in six main sites of Taiwan [35].

Geothermal sites	Temperature range (°C)	Installation potential (MWe)	Power potential (kWh/d/p)
Chinsuei, Ilan	180–220	61	0.06
Tuchang, Ilan	160–180	25	0.02
Lushan, Nantou	150–210	41	0.04
Chihpen, Taitung	140–200	25	0.02
Kinglun, Taitung	140–180	48	0.05
Mt. Tatun, Taipei	200–290	514	0.48
Total potential		714	0.67

Table 5
Statistics of power potential of the renewable energies reserved in Taiwan (unit: kWh/d/p).

	Solar	Wind	Biomass	Marine	Geothermal	Hydro	Total
Reserves	24.27	29.90	1.82	4.58	0.67	16.79	78.03
Proportion	31.3%	38.3%	2.3%	5.9%	0.8%	21.5%	100%

gy changing with the seasons), this article directly uses the data [35] for the assessment. Overall, the installation capacity of the possible development in these six main geothermal sites in Taiwan is 714MW. We adopt 90% [36] as the utilization of geothermal power plants, then the annual geothermal power generation potential in Taiwan is 714 MW $\times$ 8760 h/y $\times$ 90% = 5.63 TWh/y or 0.67 kWh/d/p.

7. Hydropower

The average annual rainfall of Taiwan is about 800 million tons (or 2500 mm) with hydropower potential of about 22,725 MW [37]. Compared to the existing total installed capacity of 1900 MW, the development proportion of hydropower in Taiwan is very low. Most people believe that the development of reservoirs in Taiwan has reached saturation, and it is unlikely that there will be any new reservoirs going to be developed. But in fact the development of water resources should not be limited to the traditional large-scale reservoirs and should be extended to various types of rivers capable of being set up small and medium sized turbines. This article will follow the analytical methods of MacKay [1] in the hydro aspects of Taiwan. By combining the drainage area and rainfall data [38] of 76 major rivers with terrain data of Taiwan [39], the information on the intersection of these two areas is obtained. By cutting the entire Taiwan into dozens of regions, and under a grid computing precision of 800 m $\times$ 800 m, the averages of topography height and annual rainfall in each region are calculated. Finally, the products of each two averages are summed up to get the estimated potential of hydropower.

In the estimation of terrain height, since current terrain map [38] is only divided into three regions, the resolution is somewhat insufficient. In order to reduce the error of the estimation of average height, this paper adopts the data of The Total Hydro-Census Report for Taiwan [37] to estimate the average height of the two regions of "100–1000 m" and "above 1000 m" to be 454 and 1838 m, respectively. According to the data of literature [40], the average height of the regions with height "below 100 m" is about 25 m (the heights of most regions of the western half are between 0 and 50 m). Regarding the estimates of the rainfall in various regions, this paper adopts the mean value of variation amounts (for example, in rainfall range of 1000–2000 mm, 1750 mm is taken). In the regions with total rainfall of 4000 mm or more, because the upper limit is unknown and the area is very small, the upper limit of 4000 mm is chosen.

Table 6
Comparison of the results generated from different studies (unit: kWh/d/p).

Country	Evaluator	Subtotal	Solar	Wind	Biomass	Marine	Geothermal	Hydro
Britain	MacKay [1]	175.5	Thermal: 13 PV (Roof) 5 PV (Farm) 50 68 (38.7%)	Land-based: 20 Offshore: 48 68 (38.7%)	24 (13.7%)	Tide: 11 Wave: 4 15 (8.5%)	1 (0.6%)	1.5 (0.8%)
Taiwan	Literatures [2–4]	48.8	Thermal: 1.19 PV: 6.08 7.27	Land-based: 1.57 Offshore: 34.48 36.05	Biomass crops: 1.67 Urban waste: 0.47 Wastes of agriculture and forestry: 3.34 5.48			
	Lin and Chen [5]	606	83.38 (land-based: 1000 km^2, offshore: 2500 km^2)	Offshore: 29.78	Thermal: 26.5 Transportation fuel: 20.33 (land-based: 20,000km^2, offshore: 9000 km^2)	208 (land-based: 200 km^2, offshore: 1000 km^2)	238 (area: 10,000 km^2, underground depth: 4–7km)	
	This article	78.03	Thermal: 1.19 PV (roof): 7.74 PV (farm): 15.34 24.27 (31.1%)	Land-based: 0.92 Offshore: 28.98 29.9 (38.3%)	Biomass crops: 0.9 Urban waste: 0.36 Wastes of agriculture and forestry: 3.29 1.82 (electric equivalence) (2.3%)	Tide: 0.23 Wave: 4.35 4.58 (5.9%)	0.67 (0.8%)	16.79 (21.5%)

From the results of calculation, it is known that the reserves energy of hydropower in Taiwan in 1 year is about 25,700 MW; namely, the energy available in 1 day is 6.17×10^8 kWh or 26.82 kWh/d/p. If the mechanical efficiency of water turbine is supposed 90% [41], then the maximal electricity available per day per person is about 24.14 kWh/d/p. Since the population of Taiwan is mostly concentrated in the region with height between 0 and 100 m, if this area is deducted from the calculation procedure, then the daily maximum of hydro energy available in Taiwan is 23.99 kWh/d/p and is then reduced to 16.79 kWh/d/p, if the evaporation of about 30% [37] is considered.

MacKay [1] divided the entire Britain into upland and lowland, and the average heights in these two areas are calculated, respectively. After the products of average height and annual average rainfall in these two areas are summed up, the total hydro reserves of the Britain is obtained. If so calculated, then the average daily share of hydro energy in Taiwan is 22.27 kWh/d/p. If mechanical efficiency of power conversion is 90%, then the potential of electricity generation will be 20.04 kWh/d/p and approximately 14.03 kWh/d/p if further considering the evaporation of 30%.

Moreover, according to the estimates of The Total Hydro-Census Report for Taiwan [37], the total hydro reserves in Taiwan (estimated by the water flow and the height of 76 rivers) are 22,725,000 kW. Under an average in 1 day, the total generation capacity is 545,400 kWh, and then the energy share per person per day is about 23.71 kWh/d/p. If the mechanical efficiency of power conversion is supposed 90%, then the electricity generation is 20.44 kWh/d/p and is approximately 14.31 kWh/d/p if further considering the evaporation of 30%. Both results of estimation [1,37] are very close to that of this article.

8. The overall potential assessment: discussion and comparison

We list the estimates of available power of seven kinds of renewable energies reserved in Taiwan in Table 5, where the wave energy and tidal energy are combined into ocean energy. It is known from the results that among the seven kinds of renewable energies, wind energy has the largest potential of development, followed by solar, hydro, marine, biomass and geothermal. The largest possible reserves of wind energy is represented by the data of Case 2 (which can get a larger value than Case 1), when considering offshore water depth less than 40 m. While regarding wave power, the limit of power conversion factor (or mechanical efficiency) of 50% of existing machine-Pelamis-is taken into account.

Please note that, in the above table, we have reserves of biomass (formerly of primary energy of 4.55 kWh/d/p) converted into equivalent electricity of 1.82 kWh/d/p under the conversion efficiency of 40%.

In order to investigate the objectivity and credibility of these results, the estimation results of MacKay [1], literatures [2–4], Lin and Chen [5] and this paper are compared as a whole in Table 6. Apart from the data of different assessment being summarized as a whole, different assessment methods are also summarized, as illustrated in Table 7. Regarding the methods of assessment, this paper is similar to literatures [2–4] (or MacKay [1]), but there are considerable differences in terms of results. First of all, the same methodology used by both is the weather data across the country contained in the Weather Bureau or the literature [8]. With a relevant geographic information and land information, the calculations are undertaken in segmented areas. And, the differences are also that the main parameters used for estimation are very different; in solar energy, the values of intensity of insolation used by both articles are different; secondly, in wind power, this paper uses small wind turbine of vertical axis of 2 kW in land area, while large wind turbine of horizontal axis of 2 MW is used in offshore area; and, other major parameters such as "utility rate" are very different from each other either.

On the other hand, in the calculation of MacKay [1], the land of the UK is not broken down to the regions, but the nationwide average densities of energy, population, land and others are used to estimate the reserves of renewable energies in the UK, therefore, the results of which are too optimistic and rough. In terms of renewable energy, the daily average reserve of the UK is three times of that of Taiwan. However, in fact, the gap should not be such large. And, the method of calculation of Lin and Chen [5] is also similar to that of MacKay [1], in which the overall nationwide parameters are also used. In addition to land area, the area of land reclamation is also taken into account in Lin and Chen [5]. At the same time, the biggest difference between Lin and Chen [5] and the other three is that the former particularly concentrates on the renewable energies of immature technologies, such as the second generation of biomass energy, deep geothermal, and ocean thermal energy conversion. Since based on the most optimistic data to estimate the total reserves, the results in Lin and Chen [5] are very large. Please refer to Section 9 for the detailed.

9. Conclusions and prospects

Since Taiwan relies on imports for 99% of energy supply, energy security constitutes the most important topic of national energy policy. The development of renewable energy resources not only can contribute the independence and autonomy of energy supply, but also can achieve the effectiveness of economic development and environmental protection-the so-called "3E". Based on the information collected from publicly available documents, the "Top-down" assessment method is adopted, and when the data are sufficient, the relevant constraints of "Bottom-up" method are also considered. Aiming to the total potential of seven kinds of renewable energies reserved in Taiwan, the overall assessment is remade.

According to the results of this assessment (as shown in Fig. 1), the reserves of seven kinds of renewable energies in Taiwan are 24.27 kWh/d/p of solar energy, 29.9 kWh/d/p of wind, 1.82 kWh/d/p of biomass, 4.58 kWh/d/p of marine, 0.67 kWh/d/p of geothermal and 16.79 kWh/d/p of hydro. The total reserved power is 78.03 kWh/d/p, which is 2.75 times of 28.35 kWh/d/p, the total electricity generation in Taiwan for 2008, so we can say that the reserves of renewable energies in Taiwan are quite abundant. However, if intending to fully develop these reserves of energies, in addition to the requirement to overcome the various difficulties of technique and implementation, the most optimistic time for the completion will be as late as 2050. However, by then, the energy supply needed may be four folds of the present's, based on the estimation of ETP 2008 of IEA, and the total reserves of renewable energies still importantly account for about 70% of national energy supply then.

Taiwan having abundant renewable energy resources is no doubt. However, after all, in Taiwan, due to dense population, lots of mountains and few of plains, and under the energy policy of economic development by low price of electricity in the long term, if intending to adopt renewable energy as main energy structure, the reliance on the development of energy technology, policy formulation and promotion efforts of government is unavoidable. In other words, the three shortcomings existing in current renewable energy-the low energy density, the high cost of power generation and the inherent constrains of supply instability-have to be overcome. Therefore, there are still a number of unbreakable barriers, if intending to fully develop the seven kinds of renewable energy sources as described in the above-mentioned. Taking

Table 7
Characteristics summary of four kinds of evaluation methods of nationwide reserves of renewable energies of mature technologies.

Country	Evaluator	Solar	Wind	Biomass	Marine	Geothermal	Hydro
Britain	MacKay [1]	Average annual insolation intensity: 110 W/m^2	Power density of offshore wind is 3 W/m^2, while that of land-based wind is 2 W/m^2	Efficiency of plants to convert carbohydrates into transportation fuel: 67% (i.e., energy loss of 33%)	Tidal current energy: 9 kWh/d/p (energy density: 3 W/m^2)	With use of the ideal Heat Engine, the best digging depth is about 15 km under the ground.	Annual rainfall of low land: 584 mm
		Roof area per capita: 10 m^2/p	Area of shallow sea: 40,000 km^2	Population density of the UK: 4000 m^2/p	Tidal energy of offshore lagoon type: 1.5 kWh/d/p with energy density of 4.5 W/m^2 and total area of 800 m^2	At depth of x, the heat flux is $(50-x)$ MW/m^2	Area of 100 m above sea level: 16,200 km^2
		Power of collector: 55 W/m^2, i.e., thermal efficiency of 50%	Area of deep sea: 80,000 km^2	Population of the UK: 60,000,000	Energy of tidal weir: 0.8 kWh/p/d	$Q_H\eta = Q_H\,(1-T_L/T_H) = (50-x)(1-278/(12.375x+278))$ MW/m^2 ($T_i = 5\,^{\circ}$C).	Annual rainfall of high land: 2278 mm
		Conversion efficiency of PV (roof-based): 20%	Coverage of wind turbine: 10% of the area of country		the UK wave energy density along the Atlantic coast: 40 kW/m	The unit electricity generated from heat engine under the ground of 5–10 km is 10 MW/m^2.	Area of 300 m above sea level: 78,000 km^2
		5% of the country to build PV farm with 200 m^2/p of installation area per capita and with conversion efficiency of 10%	Availability of wind turbine: 1/3		Only 500 km of coastline can be used		Energy per unit area = mgh
					Machine power conversion efficiency: 50%		Availability: about 1/5

Country	Evaluator	Solar	Wind	Biomass
Taiwan	Literatures [2–4]	Technical – with the use of GIS, the available land areas of counties and cities in Taiwan are calculated, and matching local insolation, the most appropriate conditions of the set up of solar facilities are calculated.	With Taiwan wind power distribution map, in height of 50 m, provided by BOE, and with the Taiwan land utilization map provided by the Department of Construction, also by using the operational platform of GIS, both maps are fitted and overlapped, such that the potential areas available for the installation of wind turbines are obtained.	The potential areas of lands suitable for the cultivation of energy crops are calculated by GIS to combine the areas of specific agricultural land, general agricultural land and fallow land.
		Feasibility – the roof areas of buildings are assessed, and the actual roof areas are multiplied by the assumed percentage of the installation of solar energy facilities in the area. Theoretical installation area of PV panels × insolation conditions × PV conversion efficiency × comprehensive coefficient, the electricity generated locally can be calculated. Therefore, the heat values of the solar hot water systems to be installed are different, as a result of the regional differences.		The potential calculation of solid waste and organic waste is based upon the compositional analyses relative to RDF and biogas.

Country	Evaluator	Solar	Wind	Biomass	Marine (OTEC)	Geothermal (deep geothermal)
Taiwan	Lin and Chen [5]	Insolation intensity: 0.85 kW/m^2 (700 kWh/m^2)	Economic zone of 10,000 km^2, offshore wind of power density of 10 MW/km^2, and capacity factor of 0.3	National woodland: about 20,000 km^2, timber obtained annually: 1200 ton/km^2, 1 kg of wood containing thermal energy of 18 MJ, and 1 ton of wood capable of being extracted 300 l of alcohol.	OTEC: cold seawater temperature of 4 °C, drainage temperature of 16 °C, volume of extracted cold water of 100 km^3/y, obtained heat of 5 EJ, thermoelectric conversion efficiency of 2.5–3.4%, installation capacity of 250 GW	Extracting 10% of heat reserved within rock of thickness of 1 km, of length and width of 10 km, respectively, and of temperature of 250 °C (rock density and specific heat are about 2.5 g/cm^3 and 1 J/(g)), annual availability of thermal energy is about 300 PJ. If thermoelectric conversion efficiency is supposed 16%, then electricity of about 13 TWh can be obtained annually.
		Sunshine hours: 2000 h		National coastline of about 1800 km, 50% of offshore area can provide 6000 ton of seaweed or algae per km^2, from which the thermal energy and alcohol extracted per unit weight of seaweed or algae are same as those of wood.		
		Conversion efficiency: 23% (GaAs) 5% of territory area (land-based: 1000 km^2, offshore: 2500 km^2)				

Country	Evaluator	Solar	Wind	Biomass	Marine	Geothermal	Hydro
Taiwan	This article	Insolation intensity: 1130 kWh/m^2-y = 129 W/m^2	Installation spacing: 3 or 6 times of rotor diameter	In addition to energy of biomass crops, energy of urban waste and wastes of agriculture and forestry are further included.	$Pwave = (1/16)(\rho g H^2 C)$	Data of shallow geothermal sites are provided by ITRI. Totally, there are 26 sites of geothermal in Taiwan with assessed reserves of 1000 MW, in which larger sites of six can be developed with reserved amount of 714 MW. The availability of geothermal power plant is 90%.	In accordance with the Taiwan terrain height map and the annual rainfall distribution maps, intersection of which is cut into dozens of regions, each area of which is estimated with grid of 800 m × 800 m. Then, in each region, the area, the terrain height, and average annual precipitation are multiplied. The estimated reserves of hydropower can be obtained by summing up the all products.
		Roof area per capita: 52.1 m^2/p, 50% of which is assumed to install solar system Efficiency of solar water heat: 50%	Large wind turbine of 2 MW (with wind speed higher than 4 m/s in 50 m height) is installed in the offshore and coastal area. Small wind turbine (with vertical axis) is installed on the roof of building and other open area (wind speed higher than 4 m/s in heights of 10 and 5 m, respectively).	The calculation method is basically same as that of Lee and Yu [4].	As long as the energy density of wave near Taiwan is known, the potential of wave energy can be calculated. $Ptide = (1/2)(\rho g H^2 A)/t$		
		PV efficiency: 10%	Map fitting manner adopted for calculation is same as that of Yang and Yu [3].		The western coasts of Taiwan are mostly flat and sandy, so it is difficult to build tidal pools there. The tidal range of Kinmen and Matsu are 5-6m. The curved coast of Penghu islands is also available for exploitation.		
		Installation area: 203 m^2 per capita					

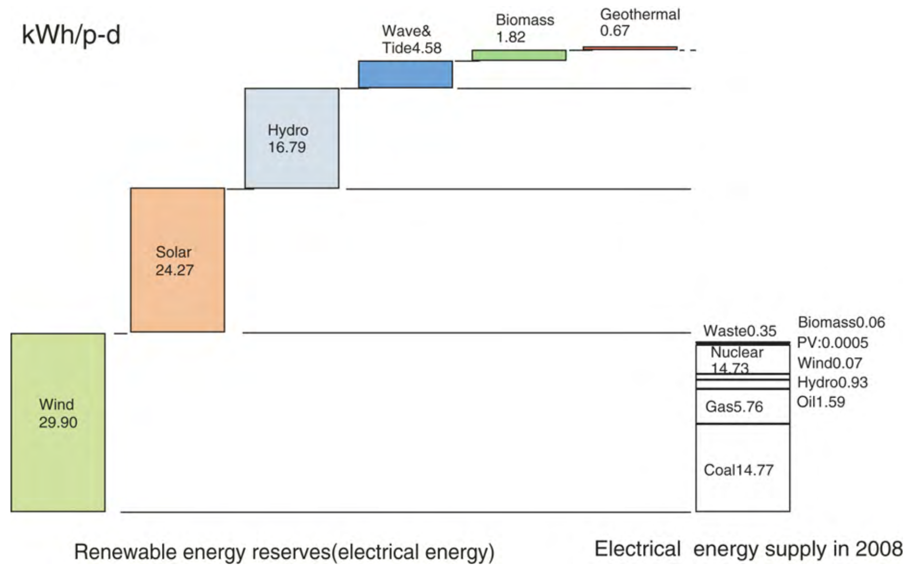

Fig. 1. Reserves of electricity of various types of renewable energies in Taiwan, compared the situation of electricity supply in 2008. In this figure, we add the 1.82 kWh/d/p of biomass (converted from 4.55 kWh/d/p of primary energy into electricity by the efficiency of 40%) to the 76.21 kWh/d/p of other six kinds of renewable energies, expressed by the form of electricity. The volume of total reserves (78.03 kWh/d/p) is about 2.75 times of 28.35 kWh/d/p-the total generation capacity of the country in 2008.

offshore wind power as example, there are many issues still involved, such as technological breakthroughs, cost reduction, formation of legal regulation, environmental assessments, reduction of natural and manmade risks, and so on, all of which are solid barriers to attract industry into investing this field. It is quite remote to comprehensively develop the entire energy of 29.90 kWh/d/p reserved in wind, based on current conditions in Taiwan, from the overall aspects of politics, economy, society and technology. Another example is the major problem faced by solar energy—the land or the roof of the acquisition. It will be very disappointed if intending to install solar device to the full scale of 24.47 kWh/d/p, particularly, due to the high cost of land in Taiwan. Further example is the development of 16.79 kWh/d/p of hydropower. Severe challenges will be faced, most notable: the deteriorating geological conditions of mountains and rivers, protest of environmental group and containment of related law, so realizing the full development is absolute difficult. Since the proportion of the total reserves of these three kinds of renewable energies is up to 91%, so if the implementation rate is 50% by overcoming the extreme difficulty, then there will be significant impact to energy structure of Taiwan. To what extent and scale can be achieved, depending on the determination of government, political wisdom of ruler, and flexibility of policy.

In addition to the seven kinds of renewable energy sources mentioned above, in fact, there are a large number of renewable energy sources with great potential to be developed in Taiwan as well, but their technologies have not been mature yet. Particularly and for example, there are four kinds: biomass energy of second generation, deep geothermal power generation, Kuroshio power generation, and ocean thermal energy conversion. If the renewable energies of these four kinds are fully developed, after the maturity of technology, then the all energy supply of Taiwan to be relied on renewable energy – the coming of "energy independence era" – should be just around the corner. Below we will discuss the potential and expected difficulties with respect to these four kinds of new renewable energies. In addition to Kuroshio power generation, the data required to estimate the reserves of other three are generally referred to those contained in Lin and Chen [5].

9.1. Second-generation biomass energy

Biomass energy of second generation is mainly comprised of two kinds of biomass-based crops: (1) fiber crops, which are inedible and can produce transportation fuels, such as ethanol or butanol; and (2) algae, which is fast-growing and does not compete with agricultural land with less consumption of production resources. Thanks to the cultivation of seaweed without use of land, these two kinds of biomass crops are very attractive to Taiwan, which is scarce of arable land. On the other hand, cellulose can be produced from a large number of agricultural waste and a variety of herbaceous plants.

According to the estimates of Lin and Chen [5], the forest land of Taiwan is about 60% of nationwide land, close to 20,000 km^2. In terms of per km^2 per year, 1200 ton of wood could be obtained. Wood per ton can be extracted 300 l of alcohol. Under this estimation, forest land of Taiwan can yield 72×10^8 l of alcohol per year.

Furthermore, territory of Taiwan is surrounded by sea, which is also the best environment for algae farming, while cell walls of algae can be a source of wood cellulose as well. If coastline of about 1000 km in the country (including offshore islands) can be developed, and to consider offshore sea area within 10 km for farming seaweed, then seaweed or algae of stem species of 6000 ton per year per km^2 could be harvested. Under the case that algae per ton can be refined 300 l of alcohol, algae can supply 180×10^8 l of alcohol annually.

The two kinds of above-mentioned biomass can totally provide Taiwan 252×10^8 l of alcohol [5], which is equivalent to heat of 50.43 kWh/d/p. If 40% is the efficiency to convert primary energy into electricity, then the total potential of electric power reserved in these biomass energies is 20.17 kWh/d/p.

9.1.1. The foreseeable difficulties

The structure of cellulose is not only too close to be dispersed or hydrolyzed, but also surrounded and protected by half-cellulose and lignin to make the hydrolysis more difficult. Therefore, physical or chemical means must be used to break up the ignocellulose structure, thereby increasing a lot of costs. Next,

enzymes with higher conversion efficiency are needed for the saccharification and hydrolysis of cellulose. Because the reaction efficiency is low and the cost is high, current enzymes are still unable to meet the needs of large-scale production. In order to achieve expected economic benefits, production technology of enzyme should be toward the directions of efficiency improvement and cost reduction.

9.2. Deep geothermal

Since the first oil crisis of 1970s, Sandia began to study the deep geothermal. Since then, advanced countries of Europe, the United States and Asia have devoted themselves into this field, so the relative technologies of mining and power generation are gradually matured. In Cooper Basin of Australia in 2006, the geothermal power plant of 3–5 MWe was completed and expanded to 40 MWe in 2009. In France of 2008, a power plant of 1.5 MWe was built and should be extended to 6 MWe in the future. In Switzerland and Germany, projects of demonstration are ongoing. Although no longer supported research activity of deep geothermal since 1995, the United States began devoting herself therein again since 2008. Overall, the commercial potential of deep geothermal is moving into the implementation phase, and the most economical sizes of plants are about between 100 and 200 MWe.

The following two subsections will describe the algorithms of rough estimation of the potential of deep geothermal in Taiwan [5].

- It is better to focus the initial development of deep geothermal on the target depth of 2–3 km. In this depth, it is possible to reach a temperature above 250 °C, particularly easy in the geothermal sites of Chinsuei, Lushan, Chihpen, and Mt. Tatun. Within 2–3 km under the ground, the rock cracks are scarce and closed well. Geologists can define fault location and size of rock on the ground or at shallow underground easily. In addition, the engineering difficulty of the construction of power plant is reduced, and the economic feasibility is significantly enhanced.
- Within 20 years, if 10% heat of hot rock of 250 °C with volume of 200 km^3 (e.g., thickness of 2 km, width of 10 km, and length of 10 km) is abstracted, then energy of approximate 19.38 kWh/d/p can be obtained. The rock density and specific heat are approximately 2.5 g/cc and 1 J/g. If 16% of thermoelectric conversion efficiency is assumed, the power of about 3.10 kWh/d/p will be given. And so on, if it is assumed that the total volume of hot rock available in Taiwan is 1000 km^3, then the electricity generation in Taiwan in 1 year will be 130 TWh or 15.48 kWh/d/p.

9.2.1. The foreseeable difficulties

Taiwan's Central Mountain Range is metamorphic rock layers of water-based and non-volcanic geothermal system. Moreover, most of the geothermal areas are shallow, and the temperatures are not high (Cheng-Hong Chen, private communication, 2010). Therefore, the energy reserves may be much smaller than the values estimated by the above information [5]. The mountains of Taiwan, located in the collision zone of Eurasian Plate and Philippine Sea Plate, belong to the geology of volcano, so there are often faults and folds in the strata, and rock is often broken due to movement. As the overall integrity of the rock mass is the necessary condition to develop deep geothermal, the detailed survey of deep geology and comprehensive assessment of engineering feasibility are necessary works for effective implementation. Just for survey work, the needed funding is substantial. In addition, with depth more than 2 km, not only the technology is difficult, but the cost is high, regarding the geological engineering and plant engineering. When encountering an earthquake fault zone, the issues of engineering reliability, construction safety, maintenance-and-operation, *etc.* have yet to be assessed in detail.

9.3. Kuroshio power generation

With east-west width of 100 km and north-south length of 400 km, the Kuroshio flows through the waters of Eastern Taiwan, and heads north by closely along the eastern coast of Taiwan. The water of Kuroshio mainly flows from the south, but there is also a part of the inflow from the east. These two flows provide the momentum needed by the Kuroshio to thrust northward and overcome various types of frictions generated from the water flows, the land, the sea bed, the internal turbulence and the atmospheric circulation flow.

The velocity of Kuroshio is affected by various factors: (1) the topography of seabed and coast (e.g., the acceleration of the Kuroshio when flowing through the channel between Taitung and Green Island); (2) the seasonal monsoons (e.g., the northeast monsoon in winter obviously weakens the flow rate of the Kuroshio); (3) other short-term factors (e.g., the invasion of typhoons, the changes of water temperature, and the change of height of sea surface caused by the change of atmospheric pressure). The quality of Taiwan Kuroshio is very good, because it has: (1) strong velocity (i.e., an average speed of 2 knots or more, large power output, and multiple choice of turbines); (2) high stability (long time of power generation); and (3) short distance from the coast (resulting in the low cost of plant construction).

The total electricity reserves of Kuroshio are subject to detailed assessment, and then making appropriate development without the affection of environment and ecology. The results of preliminary estimation show that the average kinetic energy of each segment of the Kuroshio is up to 5 GW. How much kinetic energy can be captured from each segment and how much segments are there from south to north are subject to careful calculation and analysis, however, should consider the principle-without influencing the flow stability of the Kuroshio.

Capturing energy from the Kuroshio flow without affecting its stability is possible. The Kuroshio and the Gulf Stream are known as the western intensified flows. Since they are intensified, there must be a major driving force, that is, the atmospheric circulation above waters. This atmospheric circulation is in latitude 30–45° of the North Pacific (or Atlantic) with an average wind blowing westerly (i.e., blowing from west to east). The wind in latitude 15–30° blows easterly, so the whole area of the ocean currents is brought along to rotate in a clockwise direction. This big vortex extrudes west, and strengthens the area of West Bank, resulting in Kuroshio (or Gulf Stream). The northern ocean circulation, also known as geostrophic current, is a "balanced relationship" caused by three forces, namely, "black tide flows", "Coriolis force", and "sea level difference". However, the two forces of the latter (Coriolis force, difference of height) are counterforce resulted from the flows of Kuroshio. The strength of Kuroshio flows is strong enough to support these two forces, so the momentum of Kuroshio flow is great. Therefore, the existence and large scale of the force to push Kuroshio to move are no doubt. Under conservative estimate, the power that can be developed there should be 30 GW or more, while the total installed capacity for power generation in Taiwan is 46 GW in 2008. Assuming that turbine efficiency is 50% and capacity factor is 70%, then the electricity that can be provided per annum is 91.98 TWh or 10.96 kWh/d/p.

9.3.1. The foreseeable difficulties

Kuroshio flows through east waters of Taiwan, where the depth of seabed is 500 m or over. Under this sever condition, the costs of marine works and anchoring technology relative to turbines of

deep water are high, and the risks are great as well, so careful thought and design are necessary. The impact of Kuroshio power plant on the marine ecology is bound to cause environmental concern, so there should be careful and detailed operations of assessment. Development of Kuroshio involves mining rights (belonging to the jurisdiction of the Ministry of Interior), national defense secrets (belonging to the Ministry of Defense), operating rights (belonging to Ministry of Economic Affairs), port land acquisition (belonging to local government) and so on, which are very complex and need the efforts of central government and legislature to help resolve the all executive and legislative barriers, which are the only chances to succeed.

9.4. Ocean thermal energy conversion (OTEC)

Finally, ocean thermal energy conversion is also possible for the development of renewable energy in Taiwan. The basic principle is the use of ocean surface water (with high temperature) and deep water (with low temperature) to make thermal power generation. If the temperature difference reaches 20 °C, there is economic value. In 1881, French engineer Jacques D'Arsonval first proposed the concept of OTEC. Now, NELHA (Natural Energy Lab of Hawaii Authority) is the only technological party in the world actually engaging in the research activities of renewable energy and marine science.

The principle of OTEC is similar to today's firepower and nuclear plant. First of all, water of high temperature on sea surface is used to vaporize the working fluid of low evaporation temperature (such as ammonia, propane or freon, *etc.*), then the vaporization drives turbine generators to generate electricity, and finally the cold deep-sea water is used to cool the vaporized working fluid into liquid, and so on to constitute repeated cycles. Because the seabed topography in the waters at east of Taiwan (not far from the coast) is steep, the sea depth rapidly reaches 800 m, at which the water temperature is about only 5 °C, while the temperature of surface water is 25 °C, due to the flowing through of the Kuroshio. The conditions of topography and temperature are excellent, so the potential to develop OTEC is superb. The estimates of potential of OTEC in the economic zone within 200 nautical miles are up to 250 GW. Based on different terrain, four kinds of different facilities for power generation are needed: continental shelf (the offshore platform in seabed), generator with heat exchanger, underwater floating platforms and mobile vessels.

According to the estimates of Lin and Chen [5], the water temperature of the seabed of east coast at depth of 1000 m is about 4 °C, while the temperature of water fed back into the sea is 16 °C. If the annual extraction of cold water of 4 °C is 100 km^3, then the available thermoelectric heat value is as follows.

$$\begin{aligned} &100\,\text{km}^3 \times 10^{12}\,\text{kg/km}^3 \times (16-4) \times 1\,\text{kcal/kg} \\ &\quad \times 4.2\,\text{kJ/kcal} \\ &= 166.75\,\text{kWh/d/p} \end{aligned} \tag{9.1}$$

The thermoelectric conversion efficiency is assumed 2.5%, then 4.17 kWh/d/p of electricity will be generated, roughly equivalent to 5 GW (35×10^9 kWh) of the power generation of a base load unit. If an installation capacity of 50 MW needs a cold water pipe of 10 m diameter, and the total length to install 2 sets of equipments is 1 km, each with cold water pipe of 10 m diameter, then the total length to install the cold water pipe along the eastern coast is 100 km. The total generation capacity will be up to 10 GW, equivalent to 8.32 kWh/d/p.

9.4.1. The foreseeable difficulties

Based on a series of studies, in terms of feasibility, the problems encountered in the construction of an OTEC power plant include: (a) design, manufacture and installation of cold water pipe with large diameter; (2) design and construction of large offshore platform; and (3) high efficiency of power transmission of undersea cables. In lack of these three key technologies, there is no success story in the world currently. With respect of the economic value, even if considering the economic value of aquaculture products, the cost of OTEC still cannot compete with power generation of traditional methods, like, coal, oil and nuclear power. In addition to the above technical bottlenecks, other problems, such as the needed techniques to move hundreds of thousands of tons of cold water per second and the exchange of hot and cold water in gigantic volume, a large number of disturbances to the hydrological structure of the deep sea and its effect on the marine environment, all need detailed assessment. The east sea of Taiwan is often a path for typhoon to pass through. How to avoid the destruction by typhoon is a serious topic, especially where there are long and large cold pipes installed between OTEC power plants and waters.

Table 8
List of reserves of four kinds of "new" renewable energies (unit: kWh/d/p).

	Second-Generation Biomass	Deep Geothermal	Kuroshio	OTEC
Reserved Power	20.17	15.48	10.96	8.32
Total	54.93			

We organize the preliminary estimates of the aforementioned four renewable energy of "future" in Table 8. Due to a number of data are still lack of real, actual or field measurements, the estimations of the reserves of these four renewable energies all adopt the most optimistic logic. The results of estimation are that the total reserves are 54.93 kWh/d/p, and the equivalence of primary energy is 107.07 kWh/d/p, also equivalent to 60% of 177.49 kWh/d/p of the total primary energy supply in the country in 2008.

9.5. Comparison of renewable energy reserves in all major countries

We search related sites for the relevant information of the reserves of renewable energy around the world and organize them in Table 9. The referred countries and regions are Denmark, Britain, Germany, China, India, four states of the United States, and the world. We take kWh/d/p (the energy available per person per day) as a unit of comparison, in order to avoid the loss of reasonability caused by differences of size of land area or national population. From Table 9, we can see that the reserves of different regions vary greatly. In terms of 27.5 kWh/d/p of global reserves as the average, the 78.03 kWh/d/p of reserves in Taiwan is twice more higher than the average, so the reserves in Taiwan are quite rich. Looking at the reserves of the Britain, the East of England region has reserves up to 34.5 kWh/d/p, which is much smaller than the 175.5 kWh/d/p estimated by Mackay [1] for the entire UK. It is obvious that the result of the estimation by "Top-down" method adopted by the latter is much higher than that of the former and this article, which adopt the mixed logic of "Top-down" and "Bottom-up" methods, namely, "consider the practical constraints at the same time". Denmark reserves are 81.2 kWh/d/p, which should be attributed mostly by its rich wind in North Sea. German reserves are 18.9 kWh/d/p, including wind, solar, biomass, *etc.*, and are not rich. China's huge reserves is up to 39.43 kWh/d/p, which should be attributed by the rich north-west wind and sunshine, and abundant biomass can be provided by vast nationwide agriculture and forestry lands. In contrast, the reserves of the four states of the United States are not high, and with the general impression, California and Arizona should have abundant reserves of solar

Table 9
List of the reserves of renewable energy of the countries or regions around the world.

Item	Country (or region)	Renewable energy reserves (kWh/d/p)		Description
1	Denmark [42]	81.2		Population: 5.4 million
2	The UK	A. [43]	34.5	Population: 5.4 million East Region, England
		B. [1]	175.5	Population: 60.9 million The UK
3	Germany [44,45]	18.9	Population: 82 million Excluding ocean energy	
4	China [42]	39.43	Population: 1321.29 million	
5	India [46]	1.22	Population: 1200 million Biomass: 19,500 MW Solar: 20,000 MW Wind: 47,000 MW Small hydro: 15,000 MW Marine: 50,000 MW Total: 152,000 MW	
6	California [47]	6.1	Population: 38 million Potential of the total installation capacity: 24,153 MW (including 9153 of pump storage)	
7	Massachusetts [48]	61.9 (theoretical value) 13.16 (technically feasible)	Population: 6.5 million Installation potential: 41,900 MW (theoretical value) 8700–12,900 MW (technically feasible)	
8	Florida [49]	9.89	Population: 14.6 million Installation potential: 52,700 GW (Consider the technical feasibility of 2020s target)	
9	Arizona [50]	11.0	Population: 3.6 million Consider the technical feasibility of 2025s target	
10	World [51]	27.5	Population: 6 billion Global reserves: 30,200 TWh	

energy due to significant sunshine. The reason for this contradiction might be that the assessment methods of four states adopt the logic of "Bottom-up" method, so the assessment results consider a number of practical constraints, leading to their potential value within the spectrum of 10 kWh/d/p. The estimation results of the four states of the United States are more closer to the actual estimation and are in line with the technical feasibility of the planning goals of mid-range (2020 or 2025), so we speculated that, in theory, the real values of reserves of these four states should be much larger than the data shown in Table 9, which can be verified by the data of Massachusetts. The country with the lowest reserves is India, only 1.22 kWh/d/p, probably caused by its large population and the lack of strong wind and sun.

9.6. Assess the reliability of data

As explained at the beginning of this article, a reasonable and facts-closer assessment should have two conditions: comprehensive and accurate data, and assessment logic taking into account the actual situation. However, the data adopted by this article in the assessment of the seven kinds of renewable energy sources (which are technically mature) are mostly insufficient, and detailed data required by estimation are also unavailable, so the accuracy of estimates cannot be confirmed. Therefore, in order to grasp the accurate direction of the overall estimation, this article also restructures the regional data by means of theoretical model to get the underlying assumptions, thereby highlighting the representative of the incomplete data as a main part. For example, in the assessments of wind and wave, due to the lack of raw data, this article assumes the changes of data over time as a Weibull Distribution and further hypothesizes values of parameters required in the calculation of reserves, such as shape factor and scale factor. Furthermore, the accuracy of wind speed and insolation respectively in the reserves estimation of wind energy and solar energy is also inadequate, because of the geographical changes. In order to reflect the general indicators of each renewable energies (like, solar and wind), this paper reprocesses the regional data. Further example is relative to the available land used by solar energy, wind energy, and biomass. The 70% area of the old industrial sites can be provided for the installation of PV farm, while biomass crops can be cultivated in all of the abandoned agricultural land, and wind power can be generated within 40 m of water depth in the offshore area and so on. These assumptions are very bold and can only be fulfilled by government in the full implement of the measures relative to legislation, regulation, incentive and other complementary issues. Other examples are small wind turbine with vertical axis, solar water heaters, and PV panel, all of which are adequately installed at the roof of building to save the use of land. Although we have taken into account the overall distribution of occupied area, whether they can be actually installed, such as the implementation of the allocation described in this article, is all relied on the strong policy and implementing projects of government. Further example is that since the data required in the implementation of reserves assessment of geothermal are unavailable, such as data of geological structure, formation temperature gradient, groundwater hydrology and others, this paper directly uses the value of prior assessment as the reserves of this energy.

Under the circumstances of inadequate-or-incorrect data or other practical constraints, the reserves assessment of specific

renewable energy cannot be developed in detail and fully, so the reserves assessment resulted in this paper will naturally different from the actual situation. To illustrate the rationalization of differences, we also compare the results of this paper with those of a number of previously completed assessments [1–5], as illustrated in Tables 6 and 7. Meanwhile, the renewable energy reserves in the world and in a few countries or regions [42–51] are also provided for comparison, as illustrated in Table 9, in order to strengthen reasonability of the results of this assessment.

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